THE USE OF HYDROGEN AS AN INERT GAS DURING DIVING: PULMONARY FUNCTION DURING HYDROGEN-OXYGEN BREATHING AT PRESSURES EQUIVALENT TO 200 FEET OF SEA WATER

by

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SUMMARY PAGE

THE PROBLEM

To determine whether hydrogen is a suitable inert gas to use for dives to 200 feet and to study the possible improvement in ventilatory ability with this least dense of all possible breathing mixtures.

THE FINDINGS

The maximum voluntary ventilation while breathing H_2-O_2 at a simulated pressure equivalent to 200 feet of sea water (fsw)* was found to be 14% better than on air at the surface and was improved 40%, compared with He-O_2, and 171% when compared with N_2-O_2 at 200 fsw equivalent. Similar findings were obtained for peak expiratory flow rate, peak inspiratory flow rate, forced expiratory volume in one second, and forced expiratory volume in two seconds.

*(Each time feet-of-sea-water (fsw) is mentioned, a simulated equivalent in dry atmosphere in a pressure chamber is meant.)

APPLICATIONS

The positive findings in this study should encourage further research utilizing hydrogen as an inert diving gas at medium and great depths. It could ultimately supplement or replace helium, a gas which has three potential problems: (1) respiratory limitations on exertion at great depth, (2) central nervous system effects (tremors, convulsions), and (3) eventual scarcity or depletion of helium sources.

ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of the Bureau of Medicine and Surgery Research Work Unit M4306.02-7060 --Regulation of Respiration, Circulation, and Body Temperature at Rest and During Exercise in Navy Diving Operations. The present report is No. 4 on this work unit. The manuscript was submitted for review on 11 December 1974, approved for publication on 26 December 1974 and designated as Naval Submarine Medical Research Laboratory Report Number 801.

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ABSTRACT

A review of the characteristics of hydrogen as an inert gas for use in diving is presented, with special emphasis on the extention of the respiratory limitation in diving by use of this least dense of all gases. Forced vital capacity (FVC), forced expiratory volume in one second (FEV_1), forced expiratory volume in two seconds (FEV_2), peak expiratory flow rate (PEFR), peak inspiratory flow rate (PIFR), and maximal voluntary ventilation (MVV) were measured on groups of subjects using the following gas mixtures, -- all at the equivalent of 200 fsw: four subjects breathing 97% H_2-3% O_2; two subjects breathing 97% He-3% O_2, and two divers using 97% N_2-3% O_2. The MVV on H_2-O_2 at 200 fsw was 14% better than on air at the surface, and was improved 40% compared with He-O_2 and 171% when compared with N_2-O_2 at 200 fsw. Similar findings were obtained for the following functions: FEV_1, FEV_2, PEFR, and PIFR. This is the first study in which pulmonary function has been measured during hydrogen-oxygen breathing. The values in this study for the relationship of relative gas density (ρ) to flow are in good agreement with both the theoretical and experimental values of Wood and Bryan,[39] which ranged from $\rho^{-0.41}$ to $\rho^{-0.50}$. This study showed relationships of $\rho^{-0.41}$ for MVV, $\rho^{-0.44}$ for PEFR, and $\rho^{-0.45}$ for PIFR.

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THE USE OF HYDROGEN AS AN INERT GAS DURING DIVING: PULMONARY FUNCTION DURING HYDROGEN-OXYGEN BREATHING AT PRESSURES EQUIVALENT TO 200 FEET OF SEA WATER

INTRODUCTION

There are several reasons to consider hydrogen (H_2) as an inert gas for use in diving. One of the reasons is the projected scarcity of helium (He). Recent predictions based upon reports of the Bureau of Mines concerning the available supply of helium and the projected consumption of this gas show that continuation of present usage will result in a depletion of our helium supply by the year 2000[34]. Metz in 1974 stated that it is possible that by the end of the century the United States will have to rely heavily, if not exclusively, on extracting helium from the atmosphere. He shows that this would be extremely expensive, would consume vast quantities of energy, and would have a very serious environmental impact[24]. In contrast, there exists an almost infinite supply of hydrogen.

Since hydrogen is less dense than helium, its use in diving operations should be advantageous in reducing one of the main limitations of deep diving, the respiratory impairment due to increased breathing resistance[11,17,21,22,28,38,39]. Moreover, there is some evidence suggesting that hydrogen might delay onset of the high pressure neurological syndrome. There have been only a few studies on the decompression and thermal balance characteristics of H_2. The disadvantage of the high flammability of H_2 has precluded in-depth studies and the general use of hydrogen mixtures in diving operations.

Brauer[6] exposed mice to 67 atmospheres utilizing both helium and hydrogen. He also exposed monkeys to 47 atmospheres. Helium-oxygen (He-O_2) caused some convulsive activity at this depth; hydrogen-oxygen (H_2-O_2) did not. With He-O_2[5] he observed tremors at 1200 feet sea water (fsw)* equivalent and convulsions at 1800 fsw in squirrel monkeys; with H_2-O_2, convulsions were not seen until 2400 fsw. Edel in 1972[13], successfully exposed dogs to H_2-O_2 for 20 hours at 300 fsw and 39 hours at 1000 fsw. On the other hand, Balouet, et al[2,3] and Michaud, et al[25] observed a toxic effect in rabbits after a period of time on H_2-O_2. The limited number of human exposures to H_2-O_2 has not resulted in any reported central nervous system (CNS) problems. The first of these studies was by Case and Haldane in 1941[9], in which the exposure was for five minutes at ten atmospheres. Zetterstron in 1948[45] made dives to 40 (131.2 fsw) and 110 (360.8 fsw) meters. Dives were also made to 70 (229.6 fsw) and 160 (524.8 fsw) meters by Bjurstedt and Severin in 1948[4]. Edel reported H_2-O_2 human dives with no untoward CNS effects at 200 fsw for periods up to 113 minutes in 1972[13] and 1974[10].

In regard to thermal balance, Edel[13] found that the temperature comfort zone in a dry chamber was identical (31.1-

* *fsw – feet of sea water, equivalent in a simulated situation. Each time this abbreviation appears in this paper this is a pressure equivalent in a simulated dry chamber atmosphere.*

31.6°C) for He-O_2 and H_2-O_2. Brauer, et al found a comfort zone of 30-32°C with He-O_2, and 32-34°C with H_2-O2 for squirrel monkeys[7].

Knowledge of decompression for hydrogen diving is very incomplete at this time. In HYDROX I, Edel[13] observed decompression sickness in four of eleven human dives of 10-108 minutes at 200 fsw while breathing H_2-O2. In HYDROX II, Edel[10] observed bends in four of eight dives on 97% H_2-3% O_2 at 200 fsw for 113 minutes. One major difference from other inert gases in H_2 decompression is the requirement to shift to a different inert gas at around 200 fsw to keep the H_2 percentage below the flammable level for dry chamber dives. Actual open water decompression would not have this complication. Developing safe, reliable decompression schedules for H_2 should not be too difficult.

The major disadvantage in the use of hydrogen mixtures in diving is the safety factor. The dangers can be greatly reduced by off-site premixing of H_2-O_2 and by keeping O_2 concentrations below critical percentages[12]. Oxygen must be less than 6.1% for adequate safety[16]. In case of leaks into air, H_2 levels must be below threshold levels of flammability (4.0-75% by volume)[23]. Hydrogen-oxygen exhaled below the surface in oceans or lakes would not present a flammability problem.

One purpose of the HYDROX II study was to obtain experimental data on pulmonary function during H_2-O_2 breathing for comparison with the more conventional He-O_2 and nitrogen-oxygen (N_2-O_2) mixtures. Presumably this would demonstrate the respiratory advantages of the less dense gas mixture and allow some projections for even greater depths. This is the first study of pulmonary functions during hydrogen-oxygen breathing.

METHODS

Data from eight dives to 200 fsw are reported here. This series consisted of four dives utilizing four different subjects breathing a 97% hydrogen-3% oxygen mixture, two dives and two subjects breathing 97% helium-3% oxygen, and two dives and two subjects utilizing 97% nitrogen-3% oxygen. Because of the small number of subjects, data were normalized by expressing them as percent of each subject's own control. Means and standard deviations are presented for data obtained on surface controls and hydrogen dives for four subjects. For the other conditions with two subjects, only the means of percent of control are given. All dives lasted for 2 hours (113 minutes actually at 200 fsw). The H_2-O_2 dives had a decompression of 477 minutes breathing He-O_2, He-N_2-O_2, O_2, and air. The He-O_2 dives had decompressions of 477 or 452 minutes on He-O_2, He-N_2-O_2 and air. The decompression for the N_2-O_2 dives were for 407, 472, or 493 minutes with air, N_2-O_2, and O_2.

The following six pulmonary parameters were monitored prior to, during, and after all of the eight chamber dives:

(1) forced vital capacity (FVC) in liters

(2) forced expiratory volume in one second (FEV_1) in liters

(3) forced expiratory volume in two seconds (FEV_2) in liters

(4) peak expiratory flow rate (PEFR) in liters/second

(5) peak inspiratory flow rate (PIFR) in liters/second

(6) maximum voluntary ventilation (MVV) in liters/minute

The first four values were obtained from one maneuver in which the subject inhaled completely, then exhaled as rapidly and completely as possible. The PIFR was obtained by a near maximal expiration, followed by as rapid an inhalation as possible. MVV was measured by utilizing approximately 45-65% of the FVC and as frequently as possible at this volume for 15 seconds. Each test was performed twice and the higher of two valid-appearing results was used; if any value indicated an obvious submaximal effort, a third maneuver was carried out.

A Med-Sciences Electronics Model 370 wedge spirometer, Model 280 Pulmodigitizer, Model 281 MVV Computer, and a Tektronix Model 502 X-Y oscilloscope were utilized. Only the wedge bellows was inside the chamber; the remaining equipment was outside. All subjects were trained prior to the dive so that they gave valid, reproducible results for control data. The significance of maximum effort was stressed to them for these effort-dependent tests. An oscilloscope was utilized to monitor chest position and vigorous verbal coaxing was used each time a test was performed. Surface control values were always obtained with room air, at or very near 760 mmHg pressure. All values were corrected to body temperature pressure saturated (BTPS).

Prior to any diving studies, the spirometer was flushed rapidly for six complete cycles in approximately 80 seconds. This procedure was found to remove essentially all of the room or chamber air components and to fill the spirometer with the experimental diving breathing mixtures of 97% H_2, He, or N_2 with 3% O_2, or the decompression mixtures utilized at the time.

Since the experimental gas was breathed by oral-nasal mask and the compression chamber was filled with air in most cases, a special procedure was utilized to insure that the experimental gas (97%-3% H_2-O_2, etc.) was in the spirometer as well as in the divers lungs. A two-inch rubber hose connected to the wedge bellows had a standard Collins 3-way respiratory T-valve connected to the mouthpiece end. The valve was closed and the bellows was flushed from a high pressure line of H_2-O_2, and exhausted to an overboard dump with a flash-back arrestor located outside the building. The subject was instructed to hold his breath, remove the mask, place the mouthpiece valve in his mouth, hold his nose, open the valve, perform the test, hold his breath, close the valve, and place the mask on his face. After this procedure, the spirometer was reflushed for a repetition or the next maneuver. It was then emptied, flushed with air, and opened to the atmosphere before the pressure could change; this avoided damage to the spirometer or contamination of the chamber with

hydrogen. This same procedure was utilized in the helium and nitrogen dives.

RESULTS

The first table shows MVV data for three of the four divers. The fourth subject (P.G.) could not sustain the effort for 15 seconds without coughing due to a "slight sore throat."

Maximum voluntary ventilation when breathing a H_2-O_2 mixture at 200 fsw is 14% higher than during air breathing at the surface. The comparable data for He-O_2 and N_2-O_2 breathing show decreases of 13% and 55%, respectively from surface controls.

Data on PEFR and PIFR exhibit a similar pattern as shown in Tables 2 and 3. The PEFR data is 112% of control while breathing H_2-O_2 at 200 fsw, 86% for He-O_2 at 200 fsw, and only 42% of the air surface control when breathing N_2-O_2 at 200 fsw. The PIFR values are 118%, 70% and 47% respectively, as shown in Table 3.

Table 4 shows the vital capacity during control conditions and with each of the three experimental gases at 200 fsw. The small changes in FVC are inversely related to density; the reasons are not known at this time. The FEV_1 and FEV_2 values when considered as percent of FVC or as percent of control volumes are increased from the surface air control values when breathing H_2-O_2 at 200 fsw, only slightly decreased during He-O_2 breathing, and considerably decreased during N_2-O_2 breathing at 200 fsw. This is in complete agreement with predictions based on gas density.

TABLE 1 - MAXIMUM VOLUNTARY VENTILATION (MVV) DURING HYDROX II DIVES

	AIR PRE-DIVE SURFACE CONTROL	97% H_2-3% O_2 200 fsw	97% He-3% O_2 200 fsw	97% N_2-3% O_2 200 fsw	Surface Predicted Normal Values (and Range)
SUBJECT:					
M.E.	167 l/min.	208	145	-	184(126-242)
% CONTROL	100%	125%	87%	-	
P.M.	147	154	-	75	175(117-233)
% CONTROL	100%	105%	-	51%	
S.A.	222	248	191	87	185(127-243)
% CONTROL	100%	112%	86%	39%	
MEANS	179	203	-	-	181(123-239)
S.D.	40	47	-	-	
MEANS, % CONTROL	100%	114%	87%	45%	

TABLE 2 - PEAK EXPIRATORY FLOW RATE (PEFR) DURING HYDROX II DIVES

	AIR PRE-DIVE SURFACE CONTROL	97% H_2-3% O_2 200 fsw	97% He-3% O_2 200 fsw	97% N_2-3% 0 200 fsw	Surface Predicted Normal Values (and Range)
SUBJECT:					
M.E.	9.64 1/sec.	11.26	7.67	-	9.1(7.0-11.2)
% CONTORL	100%	117%	80%	-	
P.M.	8.72	9.20	-	3.44	9.0(7.0-11.0)
% CONTROL	100%	106%	-	39%	
P.G.	9.09	10.43	-	-	9.1(7.0-11.2)
% CONTROL	100%	115%	-	-	
S.A.	10.29	11.24	9.46	4.55	9.1(7.0-11.2)
% CONTROL	100%	109%	92%	43%	
MEANS	9.44	10.54	-	-	9.1(7.0-11.2)
S.D.	.68	.97			
MEANS, % CONTROL	100%	112%	86%	42%	

TABLE 3 - PEAK INSPIRATORY FLOW RATE (PIFR) DURING HYDROX II DIVES

	AIR PRE-DIVE SURFACE CONTROL	97% H_2-3% O_2 200 fsw	97% He-3% O_2 200 fsw	97% N_2-3% O_2 200 fsw
SUBJECT:				
M.E.	7.19 1/sec	8.19	5.00	-
% CONTROL	100%	114%	69%	-
P.M.	6.72	7.85	-	3.15
% CONTROL	100%	117%	-	46%
P.G.	7.27	8.64	-	-
% CONTROL	100%	119%	-	-
S.A.	11.63	14.10	8.31	5.45
% CONTROL	100%	124%	71%	47%
MEANS	8.20	9.70	-	-
S.D.	2.30	2.96		
MEANS, % CONTR.	100%	118%	70%	47%

TABLE 4 - FORCED VITAL CAPACITY (FVC) DURING HYDROX II DIVES

SUBJECT:	AIR PRE-DIVE SURFACE CONTROL	97% H_2-3% O_2 200 fsw	97% He-3% O_2 200 fsw	97% N_2-3% O_2 200 fsw	SURFACE PREDICTED NORMAL VALUES (AND RANGE)
M.E.	4.52 l/min	4.35	4.33	-	5.06(3.90-6.22)
% CONTROL	100%	96%	96%	-	
P.M.	4.42	4.84	-	4.02	5.04(3.88-6.20)
% CONTROL	100%	110%	-	91%	
P.G.	4.02	4.06	-	-	4.66(3.50-5.82)
% CONTROL	100%	101%	-	-	
S.A.	5.35	5.69	5.65	5.32	5.20(4.04-6.36)
% CONTROL	100%	106%	106%	99%	
MEANS	4.58	4.74	-	-	4.99(3.83-6.15)
S.D.	.56	.71	-	-	
MEANS, % CONTROL	100%	104%	101%	95%	

TABLE 5 – FORCED EXPIRATORY VOLUME IN 1 SECOND (FEV_2) DURING HYDROX II DIVES

SUBJECT:	AIR PRE-DIVE SURFACE CONTROL	97% H_2-3% O_2 200 fsw	97% He-3% O_2 200 fsw	97% N_2-3% O_2 200 fsw	SURFACE PREDICTED NORMAL VALUES (AND RANGE)
M.E.	3.97 liter	3.81	3.64	-	-
% FVC	88%	88%	84%	-	83(72-98)%
% CONTROL	100%	96%	92%	-	
P.M.	3.36	3.88	-	2.28	-
% FVC	76%	80%	-	56%	83(72-98)%
% CONTROL	100%	115%	-	68%	-
P.G.	3.47	3.67	-	-	-
% FVC	87%	91%	-	-	83(72-98)%
% CONTROL	100%	106%	-	-	-
S.A.	4.46	4.91	4.33	3.09	-
% FVC	84%	86%	77%	58%	83(72-98)%
% CONTROL	100%	110%	97%	69%	-
MEANS	3.82	4.07	-	-	-
S.D.	.51	.57	-	-	-
% FVC	84%	86%	81%	69%	83(72-98)
S.D.	5.4	4.7	-	-	-
MEANS, % CONTROL	100%	107%	95%	57%	-

TABLE 6 - FORCED INSPIRATORY VOLUME IN 2 SECONDS (FEV_2) DURING HYDROX II DIVES

	AIR PRE-DIVE SURFACE CONTROL	97% H_2-3% O_2 200 fsw	97% He-3% O_2 200 fsw	97% N_2-3% O_2 200 fsw	SURFACE PREDICTED NORMAL VALUES (AND RANGE)
SUBJECT:					
M.E.	4.46 liters	4.22	4.12	-	
% FVC	98%	97%	95%	-	94(88-100)%
% CONTROL	100%	95%	92%	-	-
P.M.	3.97	4.37	-	3.19	-
% FVC	90%	90%	-	79%	94(88-100)%
% CONTROL	100%	110%	-	80%	-
P.G.	3.79	3.89	-	-	-
% FVC	94%	96%	-	-	94(88-100)%
% CONTROL	100%	103%	-	-	-
S.A.	4.95	5.41	5.15	4.46	-
% FVC	93%	95%	91%	84%	94(88-100)%
% CONTROL	100%	109%	104%	90%	-
MEANS	4.29	4.47	-	-	-
S.D.	.52	.66	-	-	-
% FVC	94%	95%	93%	82%	94(88-100)
S.D.	3.3	3.2	-	-	
MEANS, % CONTROL	100%	104%	98%	85%	

Figure 1 shows MVV, PEFR, and PIFR data plotted against percent of surface air control for various gas densities. This includes not only moist air at 1.12 grams/liter (g/l) and the three experimental 97-3% mixes used at 200 fsw, but also includes the various decompression mixtures. They were 80% He-20% O_2 at 100 fsw (1.52 g/l), air at 100 fsw (4.48 g/l), 38% He-33% N_2-29% O_2 at 90 fsw (2.94 g/l), 65% N_2-35% O_2 at 70 fsw (3.61 g/l), 65% N_2-35% O_2 at 60 fsw (3.26 g/l), air at 40 fsw (2.46 g/l), and air at 20 fsw (1.79 g/l). This figure indicates the density related results previously discussed and shows specific points for the three inert gases utilized at 200 fsw. The pattern of an increase with H_2-O_2, a slight decrease with He-O_2, and a major decrease with N_2-O_2 is easily seen.

Figure 2 shows the ratio of FEV_1/FVC and FEV_2/FVC expressed as a percentage plotted versus the gas density. A pattern similar to Figure 1 is observed, though the magnitude of the changes from control is considerably reduced. This is because a considerable portion of the vital capacity which is exhaled during the one-second (FEV_1), and an even greater portion during the two-second volume (FEV_2), occurs at lung volumes that are little affected by density, i.e., near maximal deflation or the residual position. In contrast, the peak flow rates and to

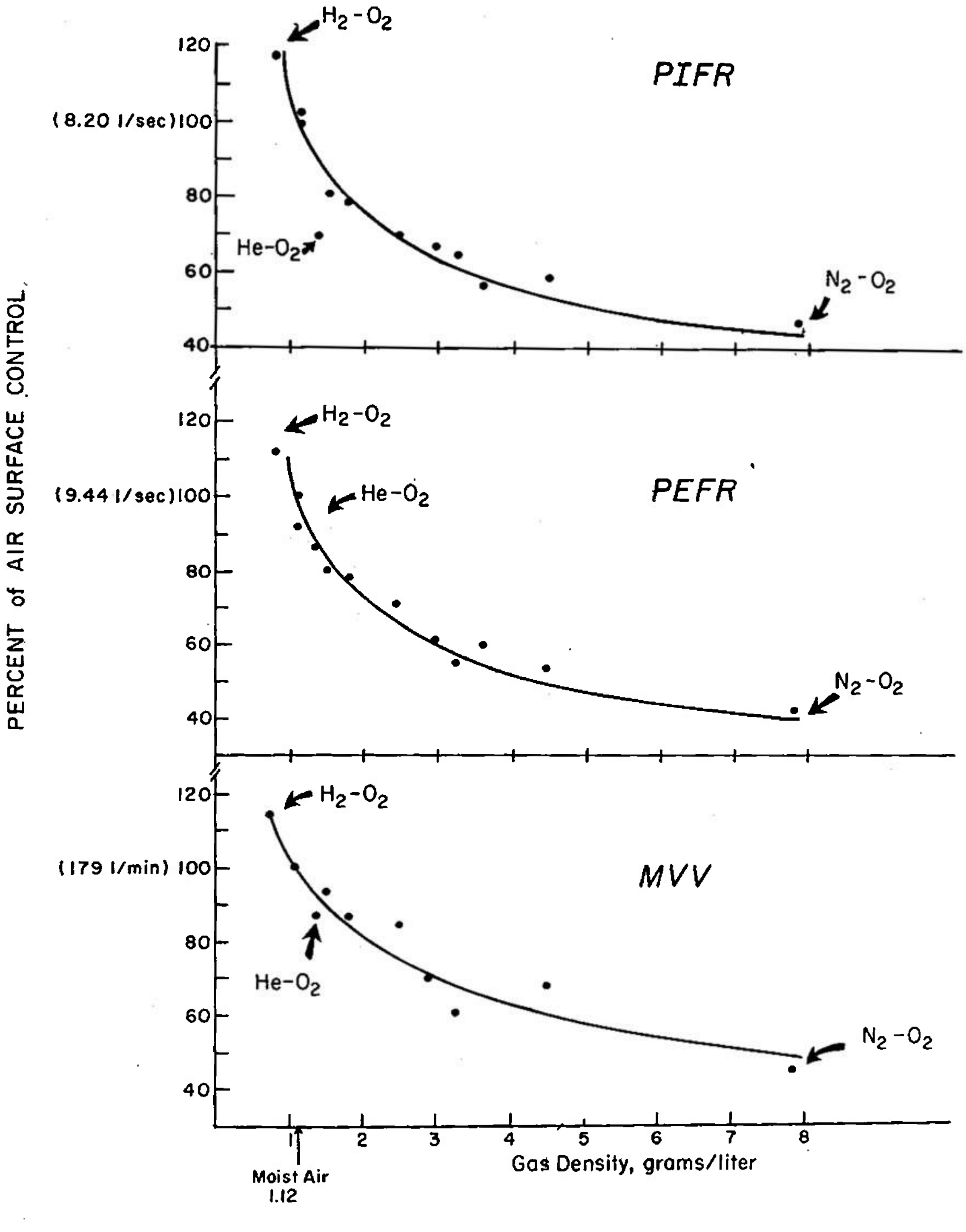

Fig. 1. Flow related pulmonary function values at various gas densities as related to values obtained with air at sea level pressure.

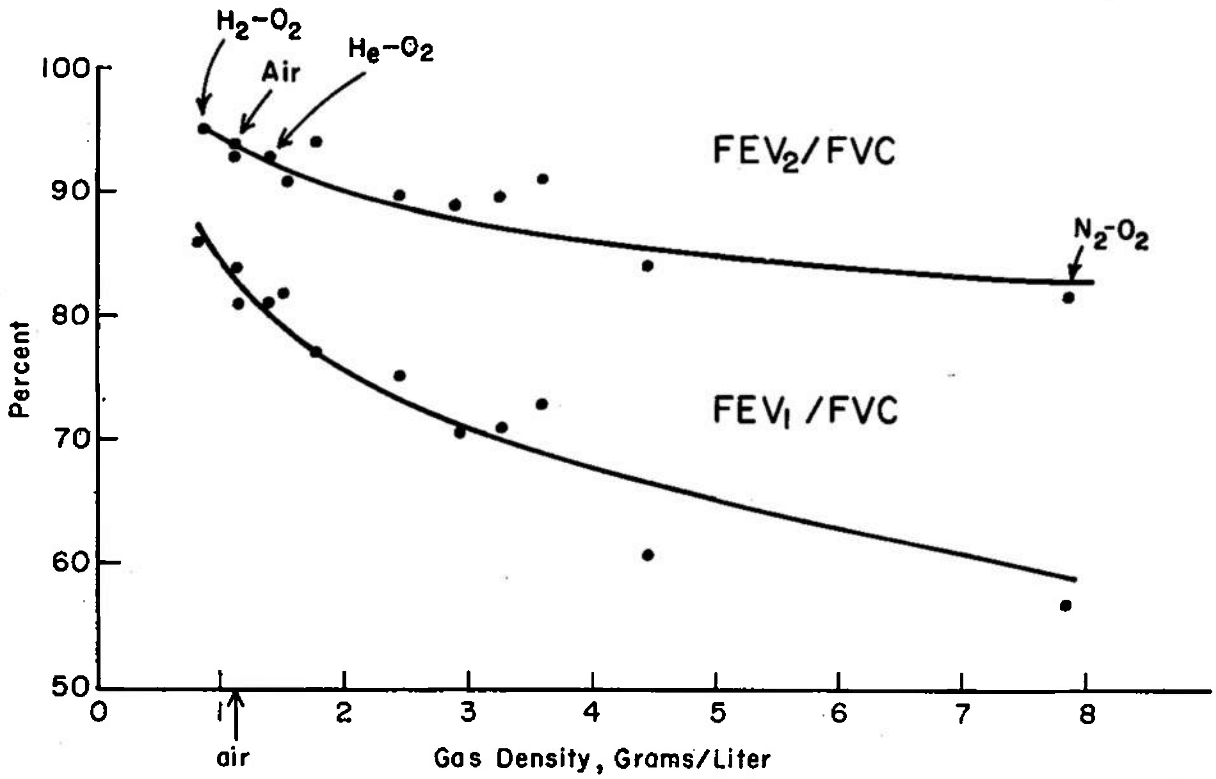

Fig. 2. The decrement in the FEV_1/FVC and FEV_2/FVC ratios at increased gas density as related to values obtained with air at sea level pressure.

a large extent the MVV maneuver (several loops per second) occur nearer maximum inflation or total lung capacity. Flow is considerably affected by density at these lung volumes.

The values for MVV, PEFR, and PIFR for pre-dive control, 200 foot H_2, He, or N_2-O_2 mixtures, all decompression mixtures, and post-dive recovery values have been analyzed as described by Wood and Bryan[39]. The percent of control was plotted on the ordinate and the gas density in gm/l on the abscissa on log-log paper. The relationship of flow at the surface to flow at increased density is described by $Y=Kx^n$ where K is flow during the surface control and the exponent (n) is the slope of the line; x is the density and Y is flow at increased density. The visual best fit (graphic) method was used. The slopes were -0.41 for MVV, -0.44 for PEFR, and -0.45 for PIFR.

Table 7 shows some data from depth-composition combinations used in this study along with data of Lanphier[18] and W. B. Wood[42] and some theoretical H_2-O_2 mixtures for 1000-6000 fsw. The density calculations assumed 0.4 atmospheres absolute (ATA) (304 mm Hg) of O_2 for the deep H_2-O_2 mixtures. The theoretical percent of air surface control for MVV values have been calculated utilizing the formula $Y=Kx^n$ where K = 179 liters/minute and n = -0.41. If this relationship holds, a diver would

TABLE 7 - DENSITIES OF VARIOUS BREATHING MIXTURES AT 37° C AND ITS EFFECT OF PULMONARY FUNCTION AS RELATED TO SURFACE CONTROL VALUES

GAS	DEPTH fsw	ATA	GRAMS/ LITER	RELATIVE GAS DENSITY (RGD)**	THEORETICAL % OF SURFACE CONTROL FROM MVV ***	% OF SURFACE CONTROL MVV	PEFR	PIFR
air, saturated	0	1	1.12	1.00	100%			
air, saturated	200	7.06	7.85	7.06	45%			
air	462	15	16.68	15.00	33%	28%(42)		
						HYDROX II		
97% N_2-3% O_2	200	7.06	7.84	7.02	45%	45%	42%	47%
97% He-3% O_2	200	7.06	1.38	1.24	92%	87%	86%	70%
97% H_2-3% O_2	200	7.06	0.81	0.73	114%	114%	112%	118%
H_2O_2*	1000	31.2	2.95	2.65	67%			
"	2000	61.6	5.34	4.80	52%			
"	3000	91.9	7.74	6.95	45%			
"	4000	122.2	10.12	9.10	40%			
"	5000	152.2	12.53	11.27	37%			
"	6000	182.8	14.93	13.43	34%	25%(18)		

* Assume O_2= 0.4 ata O_2 equivalent (304 mmHg)
** RGD, air at 760 mmHg = 1.00
*** Theoretical, assume exponent (n) - -0.412; see text
(18) Lamphier, E. H.: prediction
(42) Wood, W. B.: data

still be able to perform 34% of his surface air MVV while breathing H_2-O_2 at 6,000 fsw. This would not only support life, but allow some useful amount of work to be accomplished. The theoretical percentage values for PEFR with an exponent (n) of -0.44 and for PIFR where n = -0.45 would be only slightly lower.

DISCUSSION

It is generally agreed that the capacity of the circulatory system is the limiting factor for exercise in a healthy man at both sea level and at altitude. During diving operations, gas density increases and the limiting factor shifts from the circulatory system to the respiratory system. The exact diving depth or gas density at which this change occurs is still imprecisely defined[18,29,30,37]. This is due to increased gas density (and thus to airway resistance) and the mechanical resistance of the underwater breathing apparatus. It is reasonable to assume that the threshold can be extended to a greater depth and the respiratory limitation reduced with a less dense gas.

Judging from results obtained in the pulmonary function tests, chest x-rays, and physical examinations, all divers

had healthy lungs. The data shows that all flow-related parameters (MVV, PEFR, and PIFR) increased at 200 fsw on H_2-O_2 as compared with surface air controls. There was some reduction with He-O_2 and a considerable reduction with N_2-O_2 at 200 fsw. Ventilatory ability, as indicated by MVV with hydrogen at 200 fsw, is improved about 40% as compared with helium and 171% when compared with nitrogen. This is of considerable importance in terms of respiratory limitation on work at depth. The extent of this limitation varies according to density of breathing medium, severity of work, and lack of pathology in divers' lungs.

Of all of the available pulmonary function tests, maximum voluntary ventilation appears to be the closest to simulating actual conditions in the respiratory system during maximum exercise. The various other tests are useful to quantitate data for either clinical or research purposes but they are not as close to the natural physiological breathing pattern during exertion as is MVV. Maximum voluntary ventilation does have the disadvantage of being extremely effort-dependent and of requiring great motivation; in addition, the subject must choose the optimum combination of tidal volume and respiratory rate to get the highest possible values.

The literature contains conflicting reports on how long a maximum effort can be sustained, or more significantly, what percent of the maximum effort can be sustained for a prolonged period. Zocche, Fritts, and Cournand[46] reported that healthy young men could sustain 53% of their MVV for a period of 15 minutes. Freedman[15] reported a 4-minute MVV equal 72% of the 15 second MVV, and estimated that about 50% of the 15 second MVV could be sustained indefinitely. Shephard[32] found that the highest voluntary ventilation that the subjects were able to sustain for 15 minutes during near-maximal exercise corresponds to 70-80% of their 15 second MVV. Fagraeus[14] found that 78% (66-90%) of the 15 second MVV could be sustained until exhaustion at 3-5 minutes. Morrison and Butt[31] showed a further reduction of 5-15% due to an open circuit demand valve type of underwater breathing apparatus (UBA) at pressures of 1-8 ATA. It is suggested by Leith[19] that a five week training period for ventilatory muscles can increase sustained MVV to 80-95% of the 15 second value.

Many authors[14,26,37,39,40,41,44] have stated that increasing the density of a breathing gas had an effect on MVV, PEFR, and PIFR that shows an approximate negative power function. That is, MVV at increased density is approximately equal to MVV at sea level times $1/\sqrt{RGD}$ where RGD is relative gas density (ρ). This would result in a root function of $\rho^{-0.50}$. Miles[26] showed a slightly smaller decrease in flow rates with increasing density than the theoretical curve based on $1/\sqrt{RGD}$. Wood and Bryan have refined this relationship[39,40,41]. They reported a value of $\rho^{-0.41}$ for PEFR data in their study and stated that if all of the flow in the upstream segment were turbulent, PEFR would vary between density$^{-0.43}$ and density$^{-0.50}$ according to theoretical calculations. They believe that most of the flow in the upstream segment is non-laminar at lung volumes greater than

25% of vital capacity. The values in this study of $\rho^{-0.41}$ for MVV, $\rho^{-0.44}$ for PEFR, and $\rho^{-0.45}$ for PIFR are in agreement with both their experimental and theoretical values.

Table 7 shows the RGD for the various mixtures which we utilized plus air at 200 and 462 fsw, and H_2-O_2 at depths of 1000-6000 fsw. The reciprocal of the square root of the RGD, i.e., $1/\sqrt{RGD} \times 100$ should give the percentage of the surface air control values obtainable with these various mixtures if $\rho = ^{-0.50}$. The data for MVV, PEFR, and PIFR while breathing H_2-O_2 approximates these theoretical values. If the exponent is less than -0.50, the percentage of surface values obtained at depth would be slightly increased as is the case with HYDROX II data.

Maio and Farhi[21] show that when pressure is extrapolated to zero (no gas in airway), which results in zero airway resistance, that the intrinsic pump factors would result in a no-load flow of 14 liters/second for PEFR. They state that when breathing air at sea level, approximately 40-45% of the limitation in the maximum output in the system is due to the air itself, while the rest is due to the pump. Absence of gas would result in an approximate increase of 70% in either peak flow or MVV. It is likely that there is little or no laminar flow in the upper airways, which are the limiting factor for flow. Therefore, viscosity which has its effect during laminar flow, has a minimal significance; density which is proportional to pressure has its influence during turbulent flow and is of much greater significance[36,39].

There are differences of opinion in the literature on the depth limitation to maintain adequate ventilation to perform useful work. The joint diving studies at the University of Pennsylvania in 1971 showed that subjects can do some useful work while at 1200 fsw pressure and breathing a neon-oxygen mixture equivalent in density to He-O_2 at 4,983 fsw. These studies[35,43,44] tested 19 gas mixtures with densities ranging from 0.4 to 25 grams/liter (a range equivalent to helium from sea level to 150 ATA or 4,983 fsw). Their studies showed that physiological function at rest is not severely affected by the great density increase. Respiratory limits to forced or exercising ventilation do appear, but useful function remains even to the maximum density studied and can be predicted to persist to even much greater densities. While breathing the neon mixture at 1200 fsw (equivalent to helium at 4,983 fsw) both subjects completed the exercise at 900 kilopond-meters/minute (kpm/min.) but were unable to complete the 1200 kpm/min. level. This 1200 kpm/min. work load would have been equal to 80% of their surface maximal work capacity. It must be remembered that these subjects were not typical divers, but top university athletes, and that they were not hampered by an underwater breathing apparatus.

Anthonisen, et. al,[1] predicted some useful activity at 2,000 fsw while breathing He-O_2; Miller, et al[29] predicted the ability to do heavy work to about 1500 fsw and moderate work to 3500 fsw. Hyacinthe, et al[17] and Broussolle, et al[8] indicated that around 61 ATA (2,046 fsw) would be the limit of

ventilation at work. Fagraeus and Linnarsson[14] concluded that the highest work load that can be adequately maintained at a given air pressure up to 6.0 ATA is the load which at sea level requires a ventilation that does not exceed 60% of the 15-second MVV at the given pressure. Varene and coworkers[37] feel that the maximum work loads would be 150 watts at 400 meters (1,312 fsw), 135 watts at 500 meters (1,640 fsw), and 125 watts at 600 meters (1,968 fsw). Linnarsson and Fagraeus[20] believe that 6 ATA of air density equivalent will be close to the upper pressure limit for severe physical work even with very short work periods and low external breathing resistance. Miller[27] believes that UBA can be designed that will allow heavy but submaximal work (maximal O_2 consumption of approximately 3 1/min standard temperature pressure dry) at densities equivalent to 5-6 ATA breathing air. In 1972, Lanphier showed prediction curves for MVV of about 60 1/min at 2,500 fsw breathing He-O_2 and 50 1/min breathing H_2-O_2 at 6,000 fsw[18]. The EDU-Taylor study in April-May 1973 at 1600 fsw on He-O_2 showed no problems at rest, but some dyspnea during mild to moderate exertion[33].

Underwater breathing apparatus and diving operations add an additional load not encountered during many of these experimental studies in dry chambers with pulmonary testing equipment, such as the wedge spirometer which we used. In any case, one must conclude that ultimately, there is a respiratory limit at some depth and some work load, and that for a given depth a greater ventilation is possible with a less dense gas during extreme exertion and/or emergency situations. Therefore, a hydrogen-oxygen breathing mixture has some advantage from a pulmonary ventilation point of view, since it is the least dense of all possible breathing mixtures.

CONCLUSION

Since helium has three potential problems as an inert gas for use in diving: (1) respiratory limitation on exertion at great depth, (2) central nervous system effects (tremors, convulsions), and (3) eventual scarcity or depletion, it is concluded that further study of the use of hydrogen as a diving gas is warranted with special emphasis in the following areas: 1) respiration at rest and during strenuous exercise, 2) central nervous system effects including performance, and 3) studies at medium and great depths.

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13. ABSTRACT

A review of the characteristics of hydrogen as an inert gas for use in diving is presented, with special emphasis on the extention of the respiratory limitation in diving by use of this least dense of all gases. Forced vital capacity (FVC), forced expiratory volume in 1 second (FEV_1), forced expiratory volume in 2 seconds (FEV_2), peak expiratory flow rate (PEFR), peak inspiratory flow rate (PIFR), and maximal voluntary ventilation (MVV) were measured on four subjects breathing 97% H_2-3% O_2 at 200 fsw, on two subjects breathing 97% He-3% O_2, and on two divers using 97% N_2-3% O_2. The MVV on H_2-O_2 at 200 fsw was 14% better than on air at the surface and was improved 40% compared with He-O_2 and 171% when compared with N_2-O_2 at 200 fsw. Similar findings were obtained for the following functions: FEV_1, FEV_2, PEFR, and PIFR. This is the first study in which pulmonary function has been measured during hydrogen-oxygen breathing. The values in this study for the relationship of relative gas density (ρ) to flow are in good agreement with both the theoretical and experimental values of Wood and Bryan, which ranged from $\rho^{-0.41}$ to $\rho^{-0.50}$. This study showed relationships of $\rho^{-0.41}$ for MVV, $\rho^{-0.44}$ for PEFR, and $\rho^{-0.45}$ for PIFR.

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